

# RF Physics of ICWC Discharge at High Cyclotron Harmonics

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## ABSTRACT

Recent experiments on Ion Cyclotron Wall Conditioning (ICWC) performed in tokamaks TEXTOR and ASDEX Upgrade with standard ICRF antennas operated at fixed frequencies but variable toroidal magnetic field demonstrated rather contrasting parameters of ICWC discharge in scenarios with on-axis fundamental ion cyclotron resonance (ICR) for protons,  $\omega = \omega_{\text{CH}^+}$ , and with its high cyclotron harmonics (HCH),  $\omega = 10\omega_{\text{CH}^+}$ .

**HCH scenario:** very high antenna coupling to low density RF plasmas ( $P_{\text{pl}} \approx 0.9P_{\text{RF-G}}$ ) and low energy Maxwellian distribution of CX hydrogen atoms with temperature  $T_{\text{H}} \approx 350\text{eV}$ .

**Fundamental ICR:** lower antenna-plasma coupling efficiency (by factor of about 1.5 times) and generation of high energy non-Maxwellian CX hydrogen atoms (with local energy  $E_{\text{H}} \geq 1.0\text{keV}$ ). The additional conditioning contribution of the high energy CX flux of neutrals was evidenced.

In the present paper, we analyze the obtained experimental results numerically using (i) newly developed 0-D transport code describing the process of plasma production with electron and ion collision ionization in helium-hydrogen gas mixture and (ii) earlier developed 1-D dispersion relation solver accounting for finite temperature effects and collision absorption mechanisms for all plasma species in addition to conventionally examined Landau/TTPM damping for electrons and cyclotron absorption for ions.

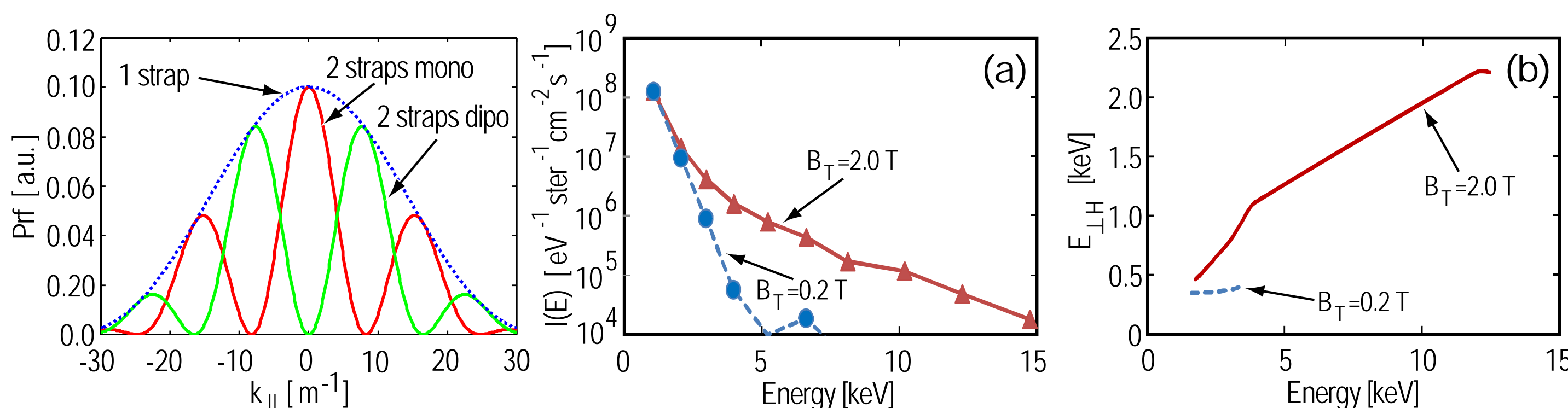
## MOTIVATION / INTRODUCTION

- The Ion Cyclotron Wall Conditioning (ICWC) technique, based on Radio-Frequency (RF) discharge ignition and sustainment with conventional ICRF heating antennas [1] is envisaged for application in ITER using the ITER main ICRF heating and current drive system [2].
- The conventional ICRF antennas with poloidal current straps are designed and optimized for heating of dense ( $n_e > 10^{19}\text{m}^{-3}$ ) target plasmas via excitation of Fast Waves (FW) with high parallel wave-numbers,  $k_{\parallel} \approx 6\text{--}10\text{m}^{-1}$ , (dipole phasing). As a result, antenna-plasma coupling efficiency is very high,  $\eta > 0.9$ . Here the antenna-plasma coupling efficiency is defined as a normalized fraction of the generator power coupled to the plasma,  $\eta = P_{\text{RF-pl}} / P_{\text{RF-G}}$ .
- Usually, FW with high  $k_{\parallel}$ -values is a non-propagative wave in low density ( $n_e \sim 10^{16}\text{--}10^{18}\text{m}^{-3}$ ) ICWC plasmas and ICRF antenna operates inefficient. To improve the antenna coupling to ICWC plasmas, several scenarios of FW excitation in low density plasmas were suggested and successfully tested [3]:
  - phasing of the antenna current straps to excite FW with low  $k_{\parallel}$  values (monopole phasing)
  - FW-SW-IBW mode conversion (MC) in RF plasmas with two ion species
  - operation at High Cyclotron Harmonics (HCH), typically  $\omega = 10\omega_{\text{ci}}$  by reducing the toroidal magnetic field value.

## EXPERIMENTAL RESULTS

### AUG ICWC DISCHARGE COMPARISON: HCH ( $\omega = 10\omega_{\text{ci}}$ ) vs ICR ( $\omega = \omega_{\text{ci}}$ )

- All (4) available ICRF antennas with two current straps in each: (i)  $f = 30\text{MHz}$ , (ii) monopole phasing (1 active strap per antenna)  $\rightarrow$  Fig.1, (iii)  $P_{\text{RF}} = 100\text{--}470\text{kW}$ , (iv)  $p_{\text{He}} \approx (2\text{--}4) \times 10^{-4}\text{mbar}$ , (v) trace hydrogen content  $p_{\text{H}_2} < 10^{-6}\text{mbar}$
- HCH,  $\omega = 10\omega_{\text{CH}^+}$  @  $B_T = 0.2\text{T}$ :** (i) high antenna coupling ( $\eta \approx 0.9$ ), (ii) Maxwellian low energy flux of CX H-atoms ( $T_{\text{H}} \approx E_{\text{H}} \approx 300\text{--}350\text{eV}$ )
- Fundamental ICR,  $\omega = \omega_{\text{CH}^+}$  @  $B_T = 2.0\text{T}$ :** (i) lower antenna coupling  $\eta \approx 0.65$ , (ii) non-Maxwellian high energy flux of CX H-atoms (local energy  $E_{\text{H}} \approx 0.8\text{--}2.0\text{keV}$ )  $\rightarrow$  Figs.2-3 and Table 1
- The additional wall conditioning contribution in high  $B_T$  was clearly evidenced for the first time [4]



**Figure 1:**  $k_{\parallel}$ -spectrum of the RF power radiated by AUG ICRF two-strap antenna in vacuum for (i) one active strap per antenna and for (ii) different phasing between two active straps.

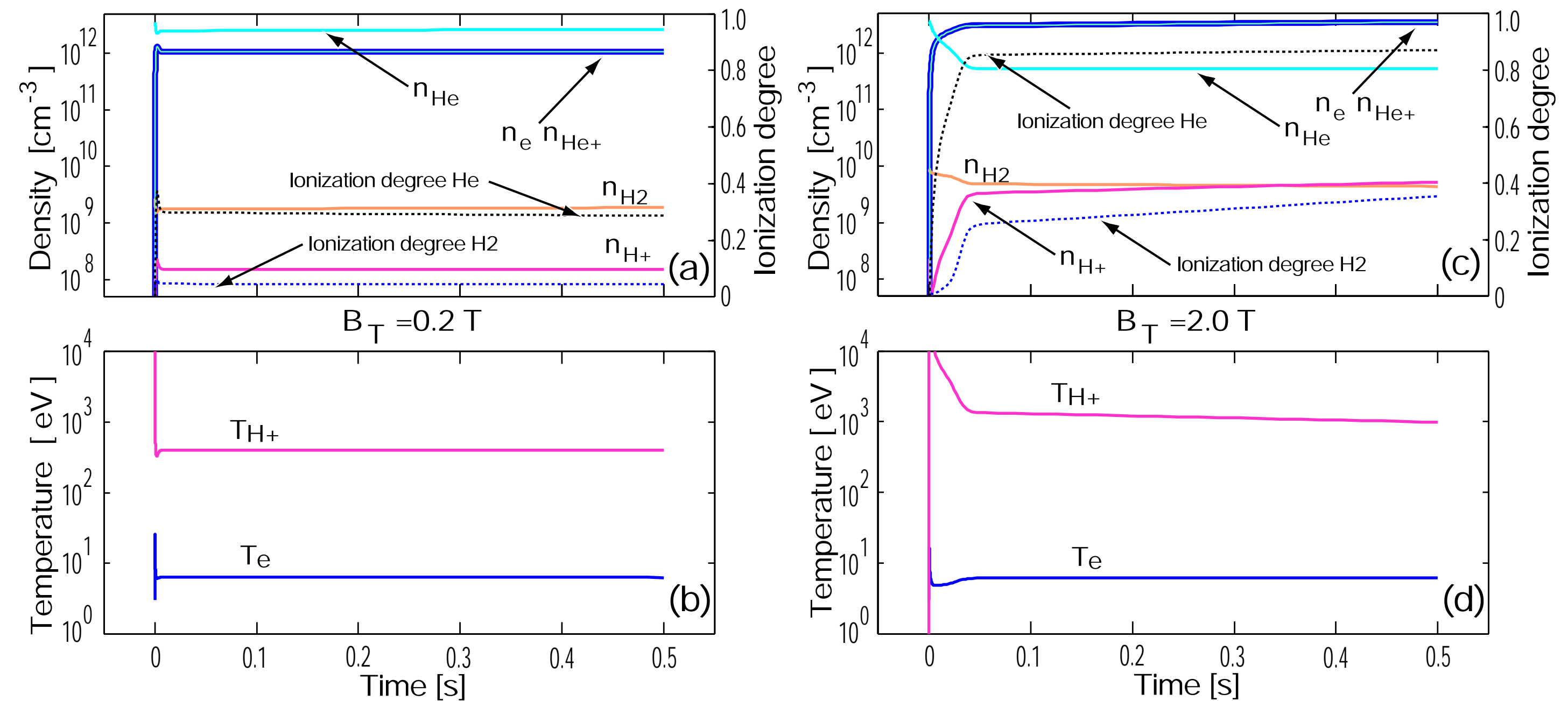
**Figure 2:** NPA detected energy spectra of the CX H-atom flux from ICWC plasmas (a) and deduced local energy of H-atoms (b) in high  $B_T = 2.0\text{T}$  (#29004) and in low  $B_T = 0.2\text{T}$  (#29012), respectively.

Toroidal magnetic field (T)	2.0	0.2
He partial pressure (mbar)	$\approx 2 \times 10^{-4}$	$\approx 2 \times 10^{-4}$
H <sub>2</sub> partial pressure (mbar)	$< 10^{-6}$	$< 10^{-6}$
RF generator frequency (MHz)	30	30
ICRF antenna phasing	monopole (1 active strap/antenna)	monopole (1 active strap/antenna)
RF pulse length (s)	10	10
Antenna coupling, $\eta$ (r.u.)	$\approx 0.65$	$\approx 0.9$
Total coupled RF power (kW)	$\approx 300$	$\approx 170$
Local energy of CX H-flux (eV)	$\geq 1000$	$\approx 350$

## NUMERICAL MODELING

### 1. SIMULATION OF ICRF PLASMA PRODUCTION IN $B_T$ PRESENCE

Plasma simulator – TOMATOR 0-D transport code [5] – is based on solution of the energy and particle balance equations for electrons, molecules (H<sub>2</sub>), atoms (H, He) and ions (H<sub>3</sub><sup>+</sup>, H<sub>2</sub><sup>+</sup>, H<sup>+</sup>, He<sup>+</sup>, He<sup>2+</sup>) in helium-hydrogen gas mixture. It takes into account: (1) elementary collision reactions (excitation/radiation, ionization (by  $\mathbf{e}$ - and  $\mathbf{i}$ -impact), dissociation, recombination, charge exchange, elastic collisions), (2) particle losses due to the finite plasma dimensions, (3) charged particle/energy confinement losses in the magnetic configuration, (4) active pumping, gas injection, particle recycling, (5) RF heating of  $\mathbf{e}$  and H<sup>+</sup>, (6) losses due to plasma impurities.



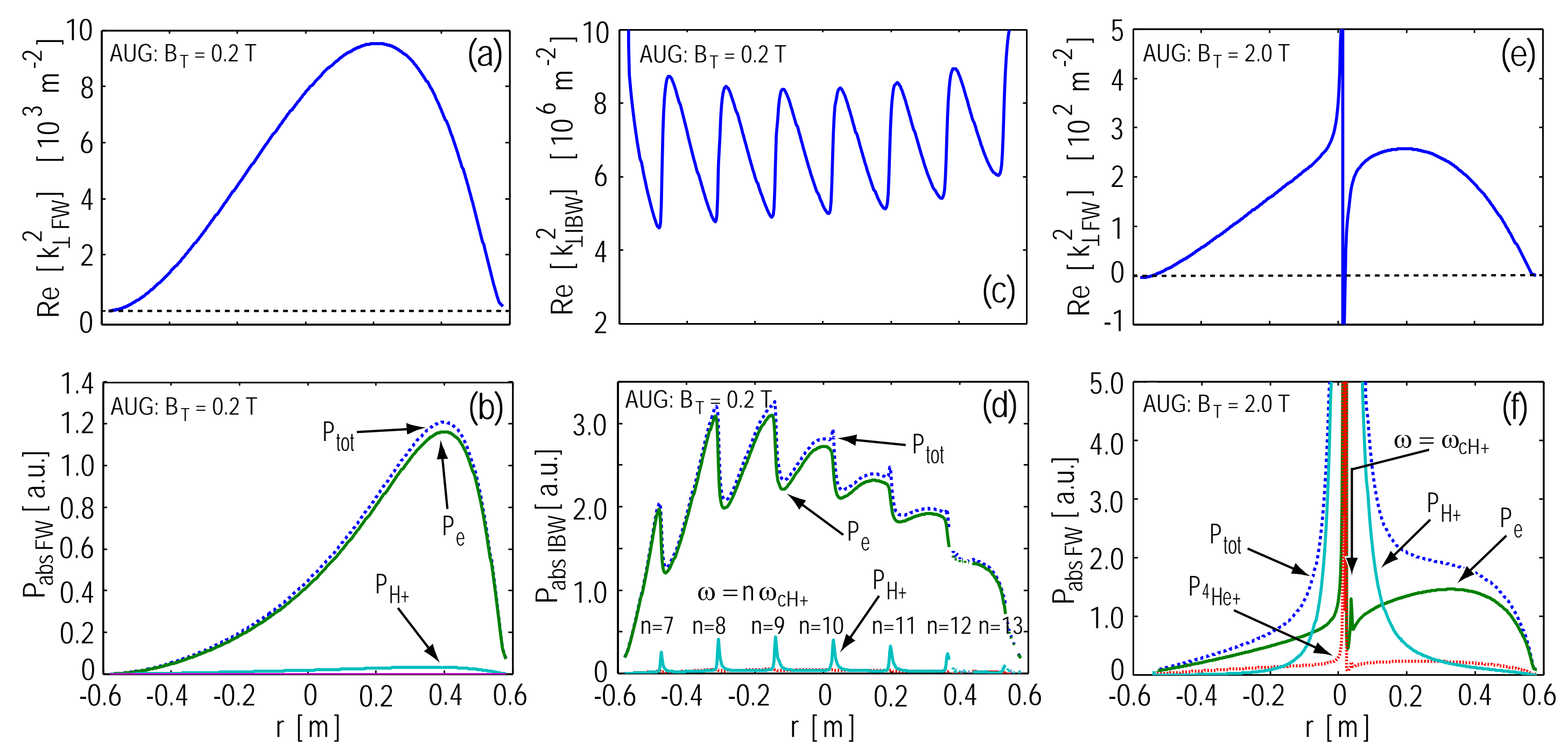
**Figure 3:** TOMATOR simulation of ICWC plasma production in AUG-like machine in low  $B_T = 0.2\text{T}$  (graphs (a)-(b)) with input parameters:  $p_{\text{He}} = 2 \times 10^{-4}\text{mbar}$ ,  $p_{\text{H}_2} = 1.5 \times 10^{-7}\text{mbar}$ ,  $P_{\text{tot}} = 175\text{kW}$ ,  $P_{\text{H}}/P_{\text{tot}} = 0.04$  and in high  $B_T = 2.0\text{T}$  (graphs (c)-(d)) with input parameters:  $p_{\text{He}} = 2 \times 10^{-4}\text{mbar}$ ,  $p_{\text{H}_2} = 5 \times 10^{-7}\text{mbar}$ ,  $P_{\text{tot}} = 300\text{kW}$ ,  $P_{\text{H}}/P_{\text{tot}} = 0.8$ .

## SUMMARY OF PLASMA SIMULATION

- For the given helium pressure, energy of protons and coupled RF power (Table 1), low density plasmas with warm protons ( $B_T = 0.2\text{T}$ ) and high energy protons ( $B_T = 2.0\text{T}$ ) may be simulated only at (i) ultra-low H<sub>2</sub>-concentration in helium, (ii) dominant *electron* heating in the low  $B_T$  and (iii) dominant *proton* heating in the high  $B_T$ .
- High energy protons generated in the high  $B_T$ -case contribute to gas ionization and support discharge even with minor fraction of the power coupled to electrons.
- Ion (proton) dominant heating regime (high  $B_T$ ) gives evidence for higher ionization degree (Fig.3c) and a noticeable contribution of high energy proton flux to the total particle flux bombarding the wall ( $\approx 3\%$ ). The latter may be beneficial for wall conditioning.

## 2. MODELING OF PLASMA WAVE DYNAMICS IN ICRF BAND

Plasma wave dynamics and RF power deposition profiles for all plasma species were modeled with a 1-D Dispersion Equation Solver [6]. It solves the dispersion equation for Maxwellian or bi-Maxwellian plasmas accounting for all Larmor radius corrections and collision absorption mechanisms in addition to conventionally examined Landau/TTPM damping for electrons and cyclotron absorption for ions. The dispersion equation solver enables studying propagation and absorption of slow waves (SW), fast waves (FW) and ion Bernstein waves (IBW) at *arbitrary* cyclotron harmonic and for *arbitrary* wavelength.



**Figure 4:** Plasma waves dispersion diagram,  $\text{Re}(k_{\parallel}^2)$ , and profiles of absorbed power calculated by dispersion equation solver for the case of AUG helium plasmas containing minor ( $< 0.4\%$ ) concentration of protons in low  $B_T = 0.2\text{T}$  (graphs (a)-(d)) and high  $B_T = 2.0\text{T}$  (graphs (e)-(f)). RF parameters:  $f = 30\text{MHz}$ , antenna monopole phasing:  $k_{\parallel} = 1.34\text{m}^{-1}$  for FW and  $k_{\parallel} = 5\text{m}^{-1}$  for IBW (Fig.1). Plasma parameters predicted by plasma simulator (Fig.3).

## SUMMARY OF RF MODELING

- FW with low  $k_{\parallel}$  values propagates in low density plasmas ( $n_e \approx (1\text{--}3) \times 10^{18}\text{m}^{-3}$ ) in both, low and high  $B_T$ -cases ( $\text{Re}(k_{\parallel}^2) > 0$ , Fig.4a,e) and provides high antenna coupling in the monopole phasing operation.
- RF power absorption at HCH ( $B_T = 0.2\text{T}$ ):** (i) *Electron-dominant* absorption via electron-neutral collisions for both, FW ( $P_e \sim 0.96P_{\text{tot-FW}}$ , Fig.4b) and IBW ( $P_e \sim 0.93P_{\text{tot-IBW}}$ , Fig.4d); Landau  $\mathbf{e}$ -damping is negligible,  $\omega / (k_{\parallel} v_{\text{Te}}) \sim 40\text{--}400$ ; (ii) Maximum of  $P_e$  for FW is shifted towards LFS (Fig.4b) and correlates with non-homogeneous plasma CCD-image; (iii) Protons are heated mainly through FW non-resonant collision damping ( $P_{\text{coll-H}^+} \sim 0.03P_{\text{tot-FW}}$ , Fig.4b); resonant IC absorption of IBW at high cyclotron harmonics for protons has a minor effect ( $P_{\text{HCH-H}^+} \sim 0.03P_{\text{tot-IBW}}$ , Fig.4d).
- RF power absorption at ICR ( $B_T = 2.0\text{T}$ ):** (i) *Ion-dominant* absorption via ion cyclotron damping of FW at the fundamental ICR for protons with minor concentration ( $P_{\text{ICR-H}^+} \sim 0.78P_{\text{tot-FW}}$ , Fig.4f) responsible for generation of high energy proton flux; (ii) Electrons absorb minor fraction of RF power via non-resonant electron-neutral collisions ( $P_e \sim 0.16P_{\text{tot-FW}}$ , Fig.4f).

## ACKNOWLEDGEMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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